Institute for Energy

Development of a General Scheme for Fuel Cycles and Life Cycles from all Energy Technologies as a Basis for the European Energy Risk Monitor (ERMON)

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1 Rationale

The European Union (EU) is facing the problem of a strongly increasing external dependence for energy. In its quest to address the issue of ***Security of Energy Supply*** along all the process from the primary energy source to the final product (heat or electricity), the European Commission (EC) must not only secure the provision of uninterrupted ***availability*** of energy products on the market, but also aim at minimising the ***safety risks*** to human health and the environment related to the use of different energy technologies for the generation and distribution of energy.

This diversity of energy systems is at the heart of the EU energy supply system, which is vital for industrial production, economic growth, employment, transportation and domestic needs.

During recent years, an increased attention has been paid by regulators, utilities, environmental groups and the general public to the comparative aspects of safety and availability of the different types of energy systems, across the different steps in their fuel and life cycle chains.

Against this background, the Joint Research Centre of the EC (DG JRC), and specifically its Institute for Energy at Petten / Netherlands (JRC-IE), initiated an activity on developing a Decision Support System for relevant stakeholders, the so-called European Energy Risks Monitor (ERMON). The **objective of ERMON** is to compare the end results of any existing safety, risk and availability study and incident/accident statistics for different energy systems across their fuel cycles and life cycles in a consistent way[1].

For the purpose of the ERMON project, the investigation of different energy technologies takes into consideration only heat and electricity production (at different scale level) at the power plant site.

The comparison will be done by mapping on an EU level energy risk sources, transport interfaces and consumption. Supplied with data on the technological, safety risk, reliability and availability aspects of the different energy technologies across their chains, the tool will form together with a cost/benefit model evaluating energy policy alternatives for each EU Member State and EU-wide the basis of the ERMON Information System, to be operated on a continuous basis as a decision support tool for EC policy services.

Within ERMON, the fuel and life cycle structure of each specific energy technology will be based on a generic model, which is described in this report. This model will constitute the first element to allow a fair and coherent risk/benefit comparison among different energy systems, a unique structure that will lead to the separate comparison of distinct and different energy systems among their own fuel and life cycle categories.

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[1] for background of JRC project ERMON see, for example:

- C. Kirchsteiger, A. Colli, COMPARISON OF ENERGY RISKS AND DEVELOPMENT OF AN ENERGY RISKS MONITORING SYSTEM (ERMON), SAFERELNET Newsletter, Issue 5, May 2004.
- C. Kirchsteiger, REVIEW OF TECHNOLOGICAL RISK MANAGEMENT IN THE EU - EXAMPLE OF THE EUROPEAN ENERGY RISKS MONITOR (ERMON) PROJECT, Presentation at Symposium on Risk Management and Cyber-Informatics (RMCI-05), Orlando, 10-13 July 2005.

To evaluate the total energy supply cycle, distinct comparative results from the two cycle categories (fuel cycle and life cycle) must then be taken into consideration for a comprehensive and clear total view.

In the larger context of ERMON, this work will be complementing and bringing forward work already started in the fields of life cycle analysis, accident and risk analysis, external costs and sustainability assessment, as well as qualification of different types of scientific/technical information (uncertainties mapping). Corresponding research co-operations are already underway. Further, co-operations with potential data suppliers, such as industry associations, have already been agreed or will be arranged in the near future.

In the present report, Chapter 1 has been dedicated to providing a rationale for this study.

The following chapter (Chapter 2) describes the processes involved in the various energy technologies: fossil, nuclear, renewable and hydrogen, with an overview of safety risk, reliability and availability related characteristics taken from various international standard references.

Chapter 3 portrays the development of a generic scheme concept applicable to all fuel and life cycles, used to base a coherent comparison among entities of the same type.

Finally, Chapter 4 offers some conclusions to this study, along with a glimpse of how the results of this report will be used in the next phase of the ERMON project.

2 Investigation of Different Energy Chains

2.1 Introduction

To generate useful heat and electrical power, a source of primary energy is required. Throughout this report, **energy source** is understood as a primary source, a substance or natural phenomenon, which can be converted through chemical, mechanical, or other means, to supply exergy, in the form of heat (thermal exergy) or electric power (as a form of mechanical exergy), as well as intermediate energy carriers, such as hydrogen or other fuels. Energy sources include coal, petroleum, natural gas, water movement, uranium, wind, sunlight, geothermal, and other sources.

With reference to the second law of thermodynamics, **exergy** is defined as available energy, the maximum amount of work that can be extracted from a physical system by exchanging matter and energy with large reservoirs in a reference state. While energy is conserved, exergy can be destroyed. While there is a constant amount of energy in the universe, the amount of exergy is constantly decreasing with every physical process according to thermodynamics second law. The content of exergy can be also used as a reliable index to indicate the quality of energy sources and to evaluate the in- and out- flows of a fuel or a life cycle with a mono-dimensional approach. In the context of the ERMON project, exergy values will be considered within the development of energy system indicators.

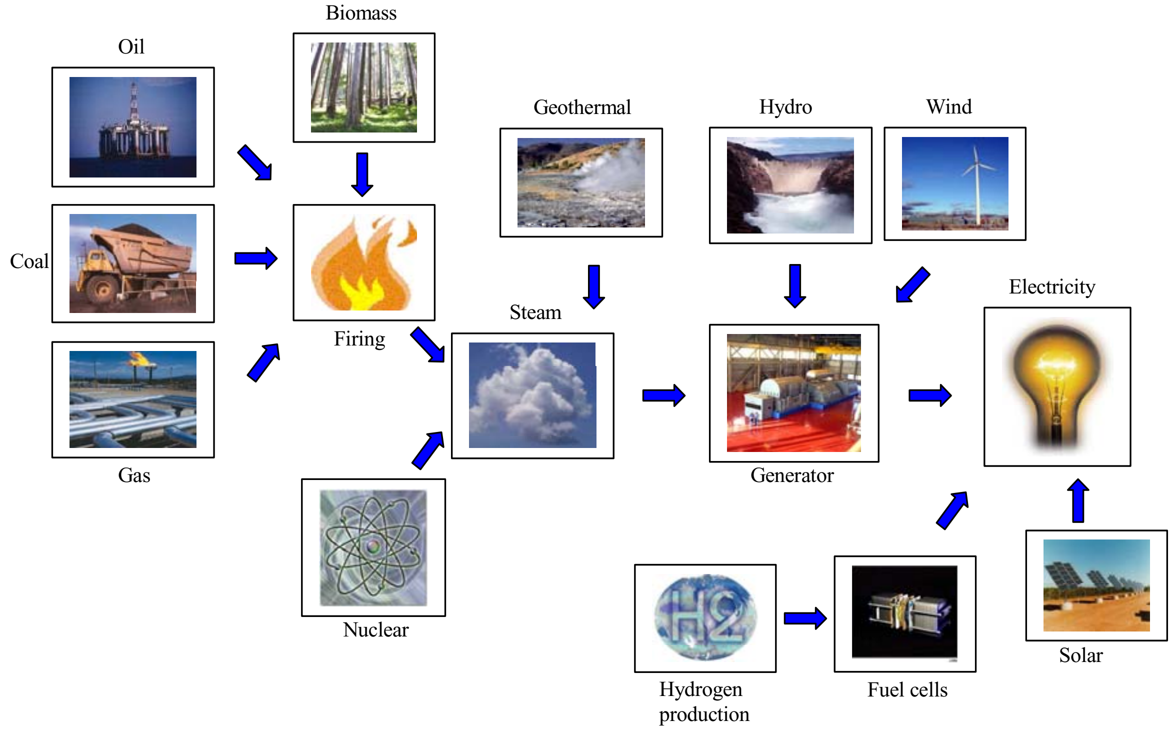
An **energy carrier** is simply any system or substance used to transfer energy from somewhere to somewhere else. For example, if energy from a nuclear power plant is used to produce hydrogen by electrolyzing water and then burned in a fuel cell to drive a car, then hydrogen is the energy carrier moving energy from uranium to the vehicle. This is usually differentiated from energy sources, whose energy was not the result of processes created by human beings but rather by various natural processes. It is also considered different from energy transmission, i.e. the wires and transformers used to move electricity from power plants to consumers.

The transformation from energy sources into useful power like heat or electricity is done through a process involving different consecutive conversion stages. Thus it is possible to see an **energy system** like a complex combination and interaction of many aspects (such as, human factors, technology, organization, policy, interactions with the environment, etc.) leading to the transformation of an energy source into useful power (that can be thermal, electrical, mechanical). It is important to highlight the human factors aspect, because people are involved in the energy system both as executors of the fuel transformation and conversion, but also as end-users.

Figure 2.1 provides a scheme, from source to end product, of a power generation process. In this scheme, fossil fuels (coal, natural gas and oil), after extraction and elaboration, are finally transported and used in fuel fired power plants, where the fuel is burnt and the resulting thermal energy is converted into electrical power by means of a steam cycle and a generator. In a nuclear power plant, nuclear fission is used to release the energy contained in atom nuclei to create high pressure steam, which then is used to drive a turbine and a generator.

Fossil and nuclear energy sources are limited in availability, and have different impacts, such as human health impacts or environmental impacts. Examples of environmental impacts are mainly greenhouse effect for the former and waste disposal for the latter. Renewable power generation technologies use infinitely available natural resources (but often not predictable, like sun or wind; furthermore in cases like, for example, biomass, the use must be sustainable and the rate of use must not exceed the growth rate), converted into electrical power or, in some cases, heat. Examples are biomass, geothermal, hydro, wind and solar power. Environmental and health impacts have to be considered also in the case of renewable energies.

Figure 2.1: Schematic diagram of power generation.



A particular case is offered by hydrogen, an energy carrier, which is generated mainly on the basis of conventional energy sources based on fossil fuels.

Electricity generated is delivered to the final loads through a network divided into two levels of transport, different according to the nominal voltage level, for instance:

1. Transmission: 750kV/433kV, 380kV/219kV and 220kV/127kV;
2. Distribution: 50kV/29kV, 10kV/5.8kV and 400V/230V.

In all of these cases, the first value is the line-to-line voltage whilst the second is the phase-to-ground voltage.

The cycles analysed throughout this report, in the context of energy supply process, can be classified according to the following definitions (see also Figure 2.2):

Fuel cycle. Along a fuel cycle of energy systems, the flow of energy passes through different linked sequential stages, from primary energy extraction, to conversion into useful outcome at a power plant and waste disposal.

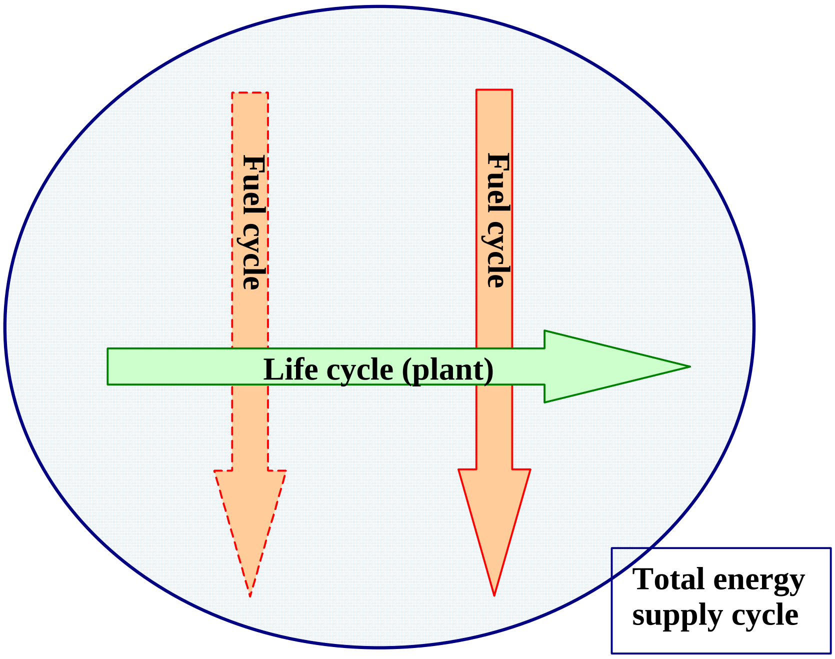
Life cycle. This includes plant life cycles. A life cycle is the sequence of events in planning, design, construction, use and abandonment or disposal during the economic or service life of a facility or a power plant; it may include changes in use and reconstruction (Table 2.1 shows average values of power plant lifespan for different energy types).

Total energy supply cycle is the union of one or more fuel cycles (considering that some power plants can be fed by different energy sources) and one ore more life cycles (considering, for example, the presence of a power plant and other possible facilities, such as refinery in the oil chain), which is important in order to obtain a complete description for evaluating a specific situation.

Table 2.1: Average power installation lifespan for different energy types.

Energy type	Sub-type	Lifespan [years]
Coal	Coal power plants	25-30
Natural gas	Combined cycle	20-30
Petroleum	Diesel engine (cogeneration use)	20
Nuclear	Pressurised Water Reactor (PWR)	60
	Modular High-Temperature Gas-Cooled Reactor (MHTGR)	30
Biomass	Wood gasification	25
	Wood gasification (cogeneration use)	15
Geothermal	Geothermal power plants	20-30
Hydro	Hydroelectric	50-100
Solar	Solar photovoltaic	25-30
	Solar thermal	20-25
Wind	Wind turbine	20-25
Hydrogen	Fuel cells (cogeneration use)	10-15

Figure 2.2: Representation of the concepts of fuel cycle, life cycle and total energy supply cycle. A power plant can also be fed by different fuels, involving different fuel cycles. In a total energy supply cycle view, more chains are normally involved.



According to the previous definitions, fuel cycles are defined in this report for the following energy carrier options:

- Coal;
- Natural gas;
- Oil;
- Nuclear (uranium);
- Biomass;
- Geothermal;
- Hydro (water movement);
- Solar (sunlight);
- Wind;
- Hydrogen.

2.2 Fossil Technologies

Fossil fuels include coal, oil and gas. They are known as ‘fossil fuels’ because they have been formed from fossilised remains of prehistoric plants and animals.

Fossil fuels covered around 80% of the world primary energy supply in 2001, reaching 83% in the OECD countries[2]. The world share of electricity generation produced through fossil fuels was 65% in 2001 [1].

The main advantages of using fossil fuels are the possibility to produce a big amount of useful power in one place, using high efficiency technologies, that in the case of a gas fired power station can reach around 60%; moreover the fuel transport to the power station is easy and well organised, like for example rail links to supply the coal.

On the other hand, there are also significant disadvantages and hazards involved with fossil technologies, such as pollution. Burning fossil fuels produces carbon dioxide, which contribute to the greenhouse effect, and sulphur dioxide (with the exception of natural gas), which is responsible for acid rains. Such polluting emissions can be reduced through appropriate filters before gases are released into the atmosphere.

Furthermore, all fossil fuel cycles can give rise to incidents and accidents with a potential harm to human health and the environment. However, the social risk originating from the fossil fuel cycle is low in comparison to other socially accepted risks.

Regarding safety risk characteristics, the PSI Report related to the ENSAD [2] database gives the following classification of fossil-chain-related events leading to potential severe accidents:

- Concerning the **coal chain**:
  - Explosions or fires in underground coal mines;
  - Collapse of roof or walls in underground or surface mines;
  - Tailing dam collapse;
  - Haulage / vehicular accidents.
- Concerning the **natural gas chain**:
  - Off-shore rig accidents;
  - Fires or explosions from leaks or process plant failures;
  - Well blowouts causing leaks;
  - Transportation accidents resulting in fires or explosions;
  - Loss of content in storage facilities resulting in fires or explosions.
- Concerning the **oil chain**:
  - Off-shore rig accidents;
  - Fires or explosions from leaks or process plant failures;

[2] Organisation for Economic Co-operation and Development. OECD countries are: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, the Slovak Republic, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States.

- Well blowouts causing leaks;
- Transportation accidents resulting in fires, explosions or major spills;
- Loss of content in storage farms resulting in fires or explosions.

According to ENSAD, in the period 1969-1996, the highest number of accidents involving fatalities was found in oil, followed by coal and natural gas.

Regarding the number of accidents involving injuries, evacuations and economical losses, oil is followed by natural gas and coal.

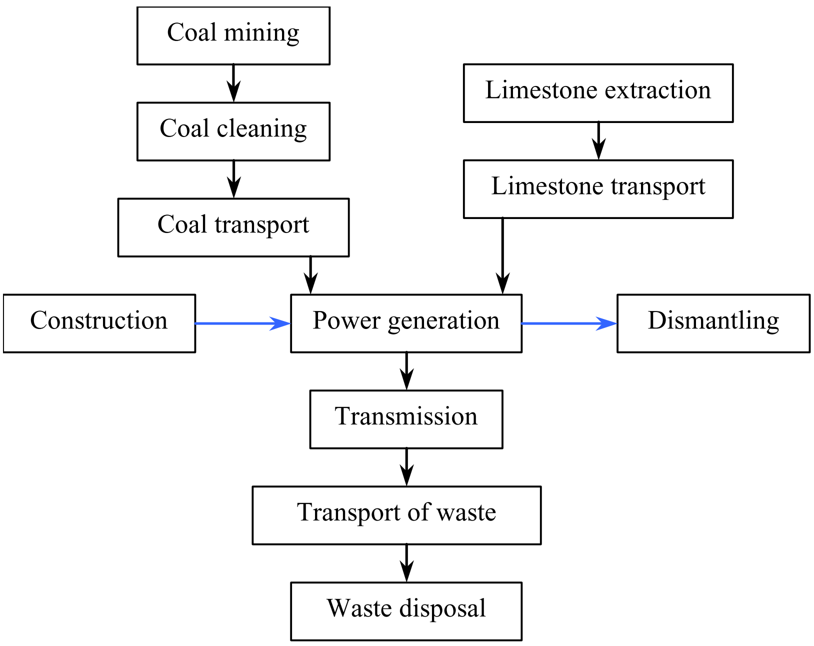
The following paragraphs briefly describe the various processes within the fuel cycles of coal, natural gas and oil.

2.2.1 Coal

Coal share related to the world primary energy supply is 24% for year 2002. Looking more in detail into electricity production, coal gave a contribution of 39% in the same year, covering 6264 TWh of the total production of 16,054 TWh [3].

The stages of the coal fuel cycle are shown in Figure 2.3.

Figure 2.3: Stages of the coal fuel cycle considered for the United Kingdom in [4]. This fuel cycle is the same also for lignite. Stages such as construction and dismantling of power generation plant are the intersection point of the power plant life cycle. For the development of the general chain scheme as purpose of this report, steps of the limestone chain are not considered as main part of the coal fuel cycle. Limestone is normally used in coal power plants for desulphurisation process.



These steps are further defined, as follows [2, 5-8]:

- Coal mining. Coal mining is divided into two processes: underground and surface coal mining (See Figure 2.4).

Figure 2.4: Coal mining processes [5].

Underground Coal Mining

Three types of underground mines

(classified according to depth and terrain type):

Shaft mines - deepest mines, with vertical access through elevator;

Slope mines - not very deep, with inclined access;

Drift mines - with horizontal entries into the coal seam from a hillside.

***Underground mining operations*:**

Cutting
Drilling
Blasting
Loading
Hauling

***Auxiliary operations*:**

Ventilation
Drainage
Power
Communications
lighting

Surface Coal Mining

Three types of surface mines

Area surface mines - usually found in flat terrain;

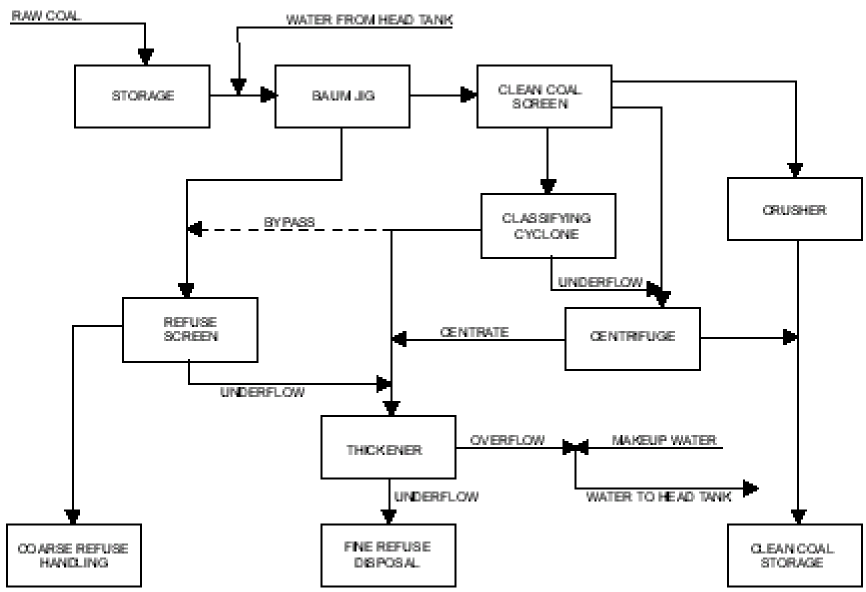
Contour mining - occurring in mountainous terrain, following the hill side;

Open pit mining - usually found where coal seams are thick, which can reach depths of about one hundred meters.

- Coal cleaning. There are two needs for coal cleaning: to remove impurities in order to boost the heat content of the coal, thereby improving power plant capacity and reducing maintenance costs and extending plant lifetime; and to reduce air pollutants, especially sulphur dioxide.

  Jig washing is the most widely used of all coal cleaning methods (see Figure 2.5); it is a wet process that gives minimal dust emissions. The lighter clean coal particulates exit at the top of the Jig and the heavier refuse particles go out the bottom. Once the coal has been cleaned, it is dewatered through the use of vibrating screens and centrifuges. The clean coal is transported to the power plant and the waste is landfilled. Coal can also be transformed into secondary fuels through the processes of coking, gasification, liquefaction and combustion, or can be converted for purposes other than the generation of fuels (for example, coal for chemical industry, production of activated carbons). Coal can be generated, without mining process, trough a bio-physical-chemical degradation called coalification.

Figure 2.5: Coal cleaning: Jig washing process [8].



- Coal transport. Coal can be transported by train, truck, or by ship over large distances. Except for mine mouth operation, coal transport by trucks is rare, while railcars are required even when barges are considered the primary method.
- Power generation, with construction and dismantling. Electricity is produced at a coal-fired fossil plant by the process of heating water in a boiler to produce steam. The steam, under high pressure, flows into a turbine, which spins a generator to produce electricity. At this stage, construction and dismantling procedures are also considered. Construction includes activities associated with land preparation, drilling and blasting, ground excavation, earth moving and the building of the power plant. The plant is decommissioned after about 30 years operation and materials like steel, aluminium and iron are recycled and used in secondary metal production operations.
- Transmission. This is long-distance electricity transmission through high voltage network.
- Transport of waste. The majority of the solid waste comes from the power plant in the form of flue gas clean-up waste and ash that can be partly recycled and partly landfilled. Transportation is mainly by truck or train.
- Waste disposal: Landfills, mines and quarries are the main destinations of not-recyclable wastes from the coal fuel cycle and from coal–fired power plants.

The analysis of severe accidents across the coal chain stored in the ENSAD database [2] shows that the number of people (workers) killed during the extraction stage is very large. The most frequent reason for severe accidents in extraction is explosion of methane in underground mines.

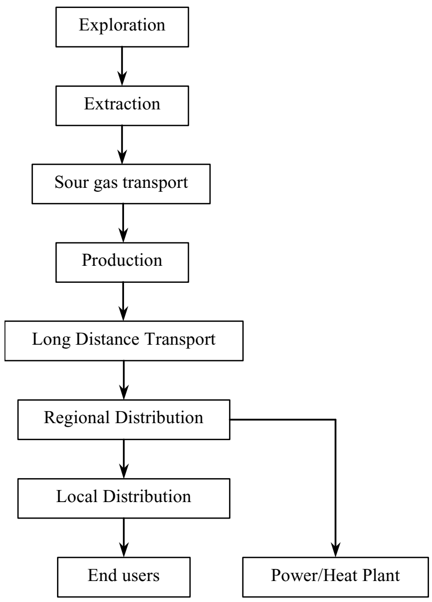
The power generation stage, with heating plant and power plant, is a relatively small contributor to severe accidents.

2.2.2 Natural Gas

Compared to other fossil fuels, such as coal and oil, natural gas is an economic, clean and efficient energy source. In the EU natural gas is the second largest energy source, behind oil. Natural gas is projected to represent one quarter of world energy supply by 2030 [9]. The fuel cycle for natural gas shown in Figure 2.6 can be described as follows:

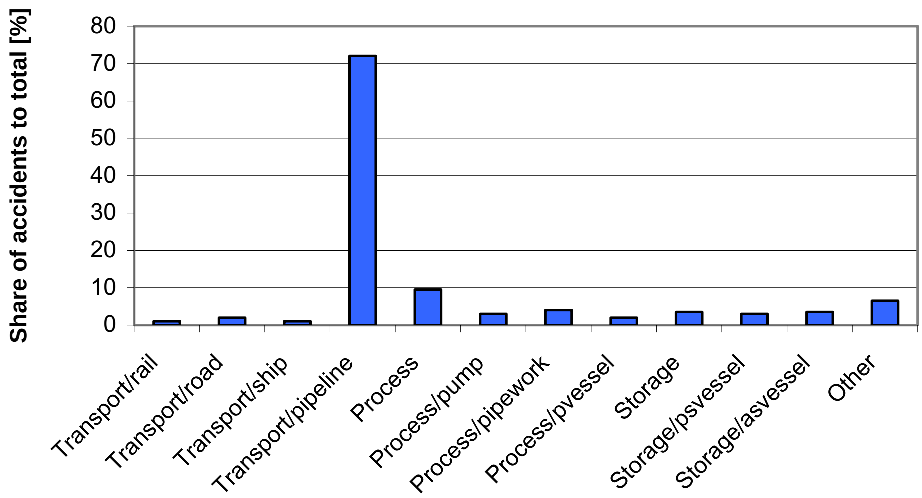
- Exploration by a team of geologists, geophysicists and micropaleontologists.
- Extraction. Drills access gas deposits and natural gas is retrieved from a productive well.
- Sour gas transport. High corrosive natural gas from the fields is transported to the nearby processing facilities through a gathering system of low pressure and low diameter pipelines. Not every gas from the field is sour gas; in some cases natural gas is directly delivered.
- Production. Natural gas is cleaned from hydrocarbon and non-hydrocarbon components.
- Long distance transport. High pressure and high diameter pipelines are used to bring natural gas to places far off from the source.
- Regional distribution. Medium-high pressure pipelines are used to distribute gas within a same region or country.
- Local distribution. Mainly low pressure pipelines distribute natural gas directly to the final users, e.g. gas for domestic use.
- End users. Referring to the fuel chain of Figure 2.6, these are mainly domestic, commercial and industrial users (e.g. glass industry, chemical industry).
- Power/heat plant. These are installations where natural gas is converted into heat and electricity. The most applied gas powered technologies are based on gas turbine combined cycle (GTCC).

Figure 2.6: Stages of the natural gas fuel cycle as presented in [2, 10, 11].



As can be seen from Figure 2.7, according to the ENSAD database [2, p.157], the by far highest share of natural gas accidents in the period 1969-1996 affects the transportation stage through pipeline, and in particular the transport on long distance with 36%. Main cause of pipeline damages is external interference due to impacts from ground work machinery.

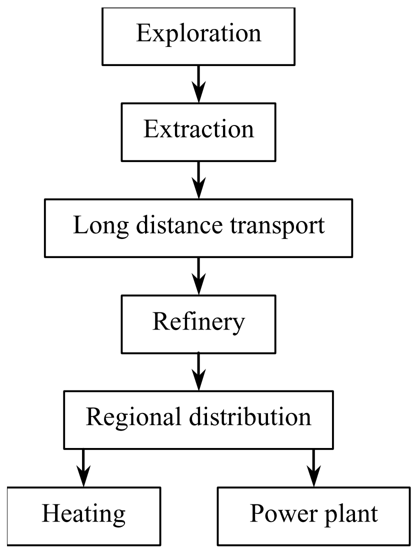
Figure 2.7: Share of natural gas accidents to total and conditions of their occurrence [2].



2.2.3 Oil

In 2002, oil contributed to the world primary energy supply for 35%. Regarding electricity production, compared to other fossil fuels, oil gave in the same year a relatively small contribution of 7% [3]. In 2003 the world oil production was 3712 Mt, with an increase of 5% compared to 2002 [1, 3]. The oil fuel cycle consists of seven different stages, as shown in Figure 2.8.

Figure 2.8: Stages of the oil fuel cycle as from [2, 11].

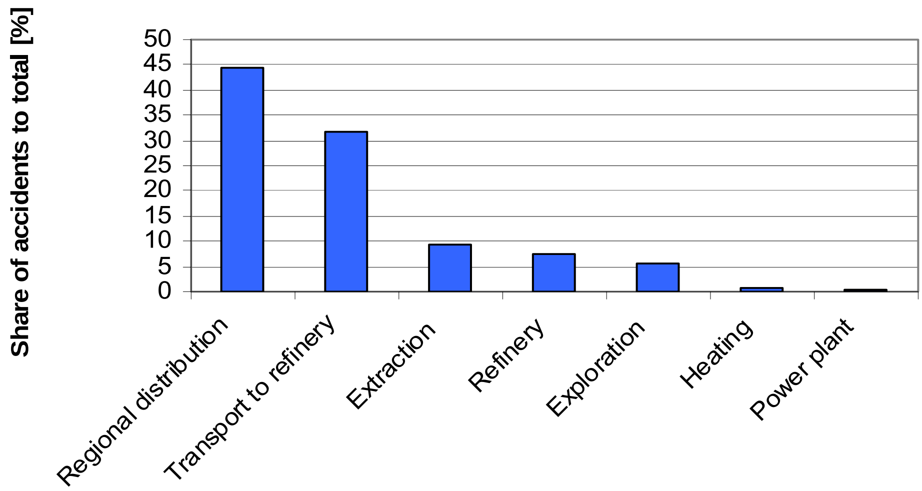


The steps of the oil chain are [12]:

- Exploration by a team of geologists, geophysicists and micropaleontologists.
- Extraction. Drills access oil deposits and oil is retrieved from a productive well.
- Long distance transport. Oil from the fields of extraction is moved to refinery mainly through pipelines and oil tankers.
- Refinery. Refineries are often huge complexes in which the crude oil undergoes several different processes (mainly separation, conversion and treatment) to remove portion of impurities in crude oil before being marketable;
- Regional distribution. Pipelines are the most common method to move finished petroleum products from refinery to customers. In addition, trucks and railroad tank cars are used to transport small-volume products.
- Heating. Industrial or household storage tanks are used for heating systems.
- Power plant. One method to generate electricity from oil is to burn oil in boilers to produce steam, which is then used by a steam turbine to generate electricity. Other methods are to burn oil in combustion turbines. In combined cycle plants, the resulting hot exhaust is used to make steam to drive a steam turbine.

As shown in Figure 2.9, according to ENSAD, the most accident-prone steps in the oil chain are regional distribution and transport to refinery, with a share of 44% and 32%, respectively.

Figure 2.9: Share of oil accidents to total across the life cycle steps [2].

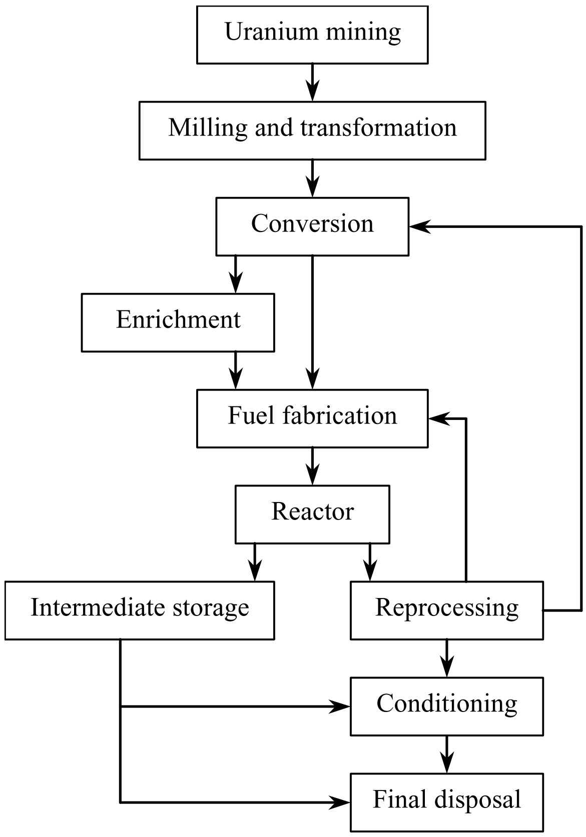


2.3 Nuclear Technologies

At the beginning of 2005, according to IAEA (International Atomic Energy Agency), 440 nuclear power plants were in operation worldwide, producing about 367 GW of electric power, covering about 16% of the world total electricity generation. 25 plants were under construction in the same period, located mainly in Asia and Eastern Europe [54].

Figure 2.10 shows the nuclear fuel cycle for a pressurized water reactor analysed for the case of Germany in the EU-funded ExternE (Externalities of Energy) study [4].

Figure 2.10: Stages of the nuclear fuel cycle considered for Germany in ExternE, Externalities of Energy, a research project of the European Commission, the first comprehensive attempt to use a consistent 'bottom-up' methodology to evaluate the external costs associated with a range of different fuel cycles [4].



The sequence of ten steps in the nuclear fuel cycle is [13-15]:

- Uranium mining. Ore (with content of about 0.2% of uranium) is mined using remote underground mining methods. The mineral deposit is wet-ground and thickened underground, and pumped as slurry to the surface. Here it is placed into purpose-built (air agitated) containers before being transported to the mill for processing. Nuclear energy resources are limited; the problem can find a solution in the use of fast reactors or molten salt reactors, with a closed-fuel-cycle process. In this way it is possible to obtain a fuel availability of thousands of years and, at the same time, a rather clean fuel cycle with no mining, milling, conversion, enriching and no high level wastes.

- Milling and transformation. This is a purification process, resulting in impure uranium oxide U_3O_8 – “yellow cake”. The uranium present in a “yellow cake” has a natural isotope composition of 0.7% U-235 and 99.3% U-238.
- Conversion. Uranium is converted into hexafluoride UF_6, which is solid at room temperature, but a gas at a slightly elevated temperature.
- Enrichment. Gas centrifuges are used for this process in USA and France, while other European countries and Russia use gaseous diffusion for enrichment. The product of the enrichment plant is UF_6 with a U-235 share of about 3 to 5%.
- Fuel fabrication. UF_6, which is chemically reactive with air or water, is converted into UO_2 – a black powder with a grain size appropriate for pressing into ceramic pellets. These pellets are then baked at very high temperatures, sized and then ready to become fuel rods. The fuel fabrication is completed by loading pellets into thin-walled zirconium alloy tubes to constitute the fuel rods. Some rods can be 5 meters long and have a diameter of a pencil. Several hundred such rods are carefully mounted with spacers in fuel elements for insertion in the reactor. The fuel load of a reactor includes normally several hundred of these fuel elements.
- Reactor. A fuel element inserted into a reactor operates at essentially full power for 4 years. Typically, every twelve months the reactor is shut down for a month so that one-fourth of the core can be replaced with fresh fuel. Some reactors are shut down after eighteen months and every time one-third of the fuel is replaced. Mainly two kinds of reactors are in use, depending on the type of moderator, *light-water reactors* and *heavy-water reactors*.
- Intermediate storage. 25 tons of the typical 100 tons of fuel in a reactor are removed every year and normally are stored in the pool at the reactor for a period from 6 months to 5 years in order to lose the fission-product decay heat.
- Reprocessing. The fuel can be reprocessed to recover plutonium.
- Conditioning. The fuel goes through this process to reduce volume and toxicity of the final waste.
- Final disposal. The fission products and the transuranic elements are stored for ultimate disposal in a mined impermeable geological repository.

The reactor stage is the most accident-affected in the nuclear chain [2, 16], which is followed by the reprocessing and transport stages (intermediate storage and final disposal).

It is important to remember that there is a qualitative difference of accidents between nuclear and other energy chains, mainly highlighted by the number of immediate fatalities compared with the number of latent (delayed and indirect) fatalities (fatalities can be the consequence of an incident/accident or of the toxicity of uranium compounds).

2.4 Renewable Technologies

Renewable energy technologies are contributing more and more to heat and electricity generation. According to the 1997 so-called EU White Paper [17] the target for renewable energies in the EU is to cover 22% of electricity and 12% of the total energy demand by 2010. In addition, renewable energies are relatively clean power sources, as they provide energy that has much lower, or even no, carbon dioxide emissions when compared to traditional fossil fuels [18, 19].

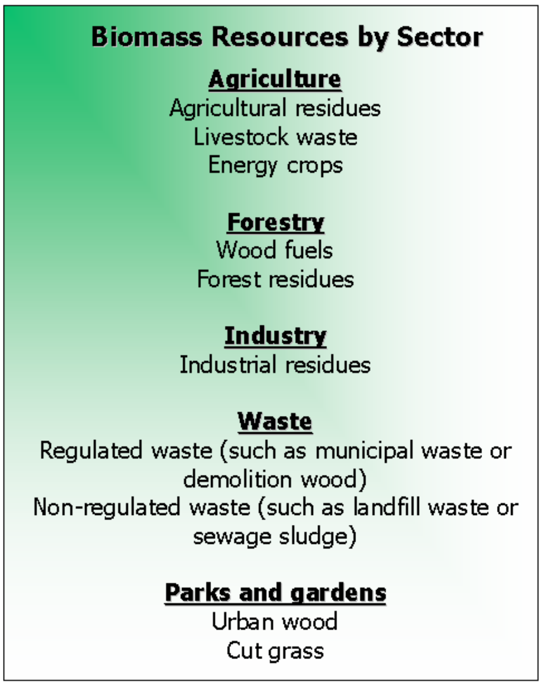
This section is dedicated to describing five types of renewable energy technologies: biomass, geothermal, hydro, solar and wind.

2.4.1 Biomass

According to the definition reported in the European Directive 2001/77/EC, '*biomass*' shall mean the biodegradable fraction of products, waste and residues from agriculture (including vegetal and animal substances), forestry and related industries, as well as the biodegradable fraction of industrial and municipal waste [20]. At the end of 2003 the electricity produced from biomass in the EU-15 was about 45 TWh/a [19].

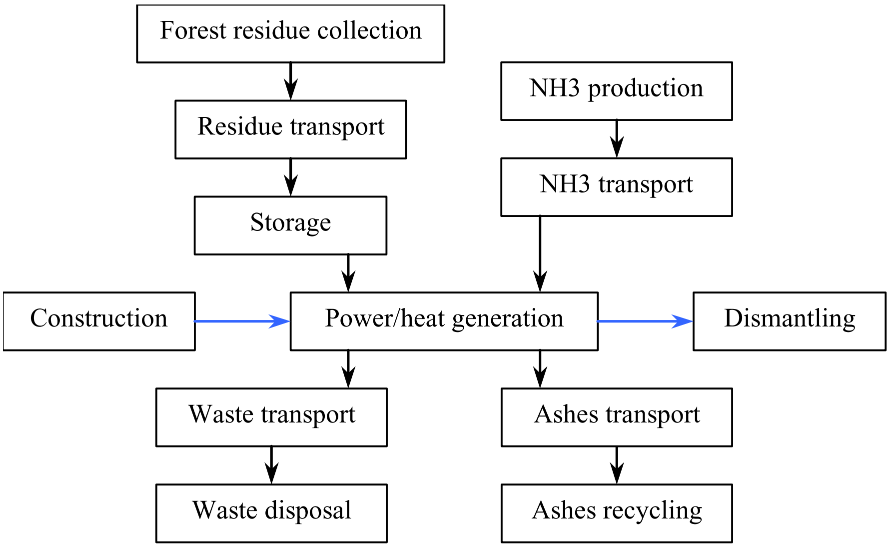
Biomass fuel resources can come from different sectors, as shown in Figure 2.11:

Figure 2.11: Biomass fuel resources divided by sector.



The following Figure 2.12 provides a scheme of the stages in the biomass life cycle.

Figure 2.12: Example of the biomass fuel cycle (biomass combustion) considered for Sweden in ExternE, Externalities of Energy, a research project of the European Commission, the first comprehensive attempt to use a consistent 'bottom-up' methodology to evaluate the external costs associated with a range of different fuel cycles [4]. This is a thermo-chemical process. Stages such as construction and dismantling of power generation plant are the intersection point of the power plant life cycle. For the development of the general chain scheme as purpose of this report, steps of the NH3 chain are not considered as main part of the biomass fuel cycle. NH3 is normally used in biomass power plants as pollution abatement material.



The steps of the first chain are [4, 21, 22, 23, 24]:

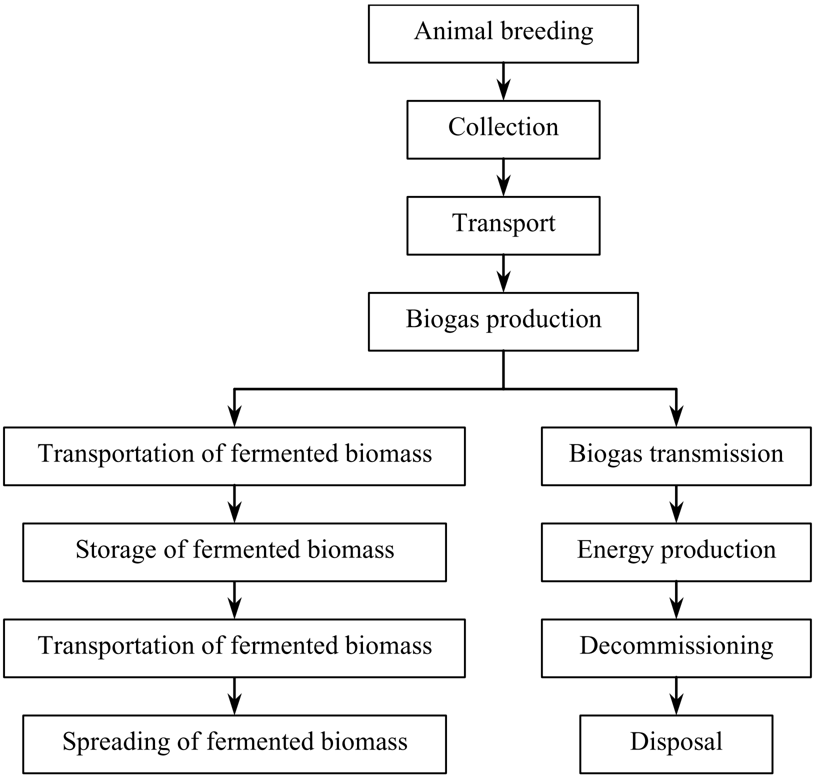
- Forest residue collection. Forest residues include underutilized logging residues, imperfect commercial trees, dead wood, and other non-commercial trees that need to be thinned from crowded, unhealthy, fire-prone forests or any other leftover plant material after cutting.
- Residue transport. This is residue that is transported with conventional forest operations equipment (trucks, loaders, forwarders).
- Residue processing. In processing facilities, biomass undergoes a primary energy conversion processes. Primary energy conversion processes are divided into thermo-chemical (combustion, gasification and pyrolysis) and biochemical (anaerobic digestion). Like direct combustion, gasification is a high-temperature thermo-chemical conversion process, but the desired result in this case is the production of a combustible gas, instead of heat. This is achieved through the partial combustion of the biomass material in a restricted supply of air or oxygen, usually in a high-temperature environment of around 1200-1400 C°. Pyrolysis is thermal decomposition occurring in the absence of oxygen, and it is also the first step in combustion and gasification processes where it is followed by total or partial oxidation of the primary products. The goal of pyrolysis is to produce a liquid fuel, termed bio-oil or pyrolysis oil, which can be used as a fuel for heating or power generation. The most common biochemical process to convert high-moisture biomass is anaerobic digestion, where bacteria produce biogas. Several liquid biofuels (bioethanol, biodiesel, biomethanol) can also be produced by biochemical conversion.
- Storage. This stage includes storage facilities for solid, liquid or gas types of biomass-derived fuels.

- Power generation, with construction and dismantling. Solid, liquid and gaseous biomass fuels can be used for small-scale applications and converted into heat and, through mechanical energy, into electricity, or can be used as transport fuels. Secondary energy conversion technologies include: steam engines, steam turbines, stirling engines, internal combustion engines, gas turbines, micro turbines and fuel cells.
- Waste transport: At this stage, waste is transported mainly by truck or train, but shipping can also be used.
- Waste disposal: This stage is where the waste is stored in landfills.
- Ashes transport: Ashes are transported mainly by truck or train, but at times, shipping can also be used.
- Ashes recycling. Combustion ashes are recycled as raw materials or for the production of cement.

The fuel cycle shown in Figure 2.12 is an example of thermo-chemical conversion of biomass, while the fuel cycle in Figure 2.13 is a case of anaerobic digestion using organic animal waste.

Anaerobic digestion is a low-temperature biochemical process, through which a combustible gas (biogas) can be produced by digestion bacteria from biomass feedstock and can be used in secondary conversion technologies like gas engines and turbines.

Figure 2.13: Example of the biogas chain (digested biomass) considered for Denmark in ExternE, Externalities of Energy, a research project of the European Commission, the first comprehensive attempt to use a consistent 'bottom-up' methodology to evaluate the external costs associated with a range of different fuel cycles [4]. This is a biochemical process.



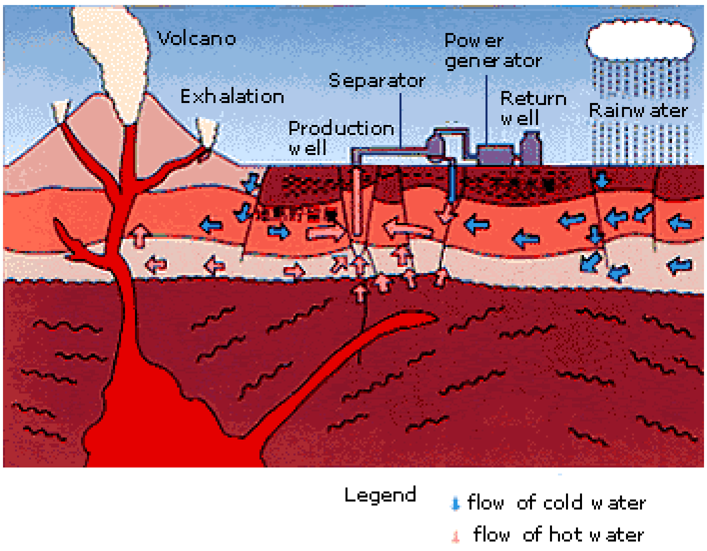
This biomass analysis has been based on two fuel cycles, respectively representing a case of biomass combustion in Sweden and a biogas cycle in Denmark. According to ExternE (Externalities of Energy), in the case of Sweden the impact of main interest is related to air pollution, while incidents affecting occupational health are considered negligible, as they are not common enough. In the case of Denmark, accidents affecting occupational and public health are taken into consideration. Threats to occupational health can come from the stage of material production, such as biogas production, while threats to public health can come from the transportation step in the chain, causing consequences to drivers, pedestrians, cyclists and houses along the road [4].

2.4.2 Geothermal

Geothermal is a source of energy available as heat emitted from within the earth's crust, usually in the form of hot water or steam (hydrothermal fluids) or hot dry rock applications. It is exploited at suitable sites for electricity generation after transformation or directly as heat for district heating, agriculture, etc. Utilization of geothermal energy is most favourable where the energy concentration is highest, namely at volcanic or geothermal zones of the Earth. The amount of heat energy stored in the bedrock in the upper 3 km of the crust, has been estimated to be some 43×10^{24} J [25].

Data available for 1997 show that the electricity generation and the direct use of geothermal energy amount, respectively, to 8,021 MW-e with 43,756 GWh/a, and 9,704 MW-th with 35,098 GWh/a [25].

Figure 2.14: Representation of the geothermal chain [26].



The sequence of steps in the geothermal fuel cycle from Figure 2.17 is [27, 28, 29]:

- Exploration. geological, hydrogeological, geophysical, and geochemical techniques are used to identify and quantify geothermal resources. Geothermal exploration addresses at least nine objectives, as indicated in Figure 2.15.

Figure 2.15: Objectives of geothermal exploration.

Objectives of Geothermal Exploration

1. Identification of geothermal phenomena.
2. Ascertaining that a useful geothermal production field exists.
3. Estimation of the size of the resource.
4. Classification of the geothermal field.
5. Location of productive zones.
6. Determination of the heat content of the fluids that will be discharged by the wells in the geothermal field.
7. Compilation of a body of data against which the results of future monitoring can be compared.
8. Assessment of the pre-exploitation values of environmentally sensitive parameters.
9. Determination of any characteristics that might cause problems during field development.

- Drilling. Once potential geothermal resources have been identified, exploratory drilling is carried out to further quantify the resource. Because of the high temperature and corrosive nature of geothermal fluids, as well as the hard and abrasive nature of reservoir rocks found in geothermal environments, geothermal drilling is much more difficult and expensive than conventional petroleum drilling. Typically, geothermal wells are drilled to depths ranging from 200 - 1,500 m depth for low and medium temperature systems, and from 700 - 3,000 m depth for high temperature systems. The well allows the geothermal fluid to pass into a pipe and to be used in the plant.
- Extraction. The geothermal fluid is led from the well head to a flash separator which separates the liquid from the saturated steam and non condensable gases.
- Distribution The distribution of geothermal fluid is normally on plant site through pipelines.
- Power generation, with construction and dismantling. The geothermal plant uses steam to drive turbines to generate electricity. The hot water from a geothermal source can be also used to heat a secondary working fluid, such as ammonia or isobutane, in a closed-loop system. The working fluid is vaporized in a heat exchanger and is then used to drive a turbine-generator. There are three basic types of geothermal power plants, according to the temperature and pressure of the reservoir, as shown in Figure 2.16.

Figure 2.16: Types of geothermal power plants.

Geothermal Power Plants

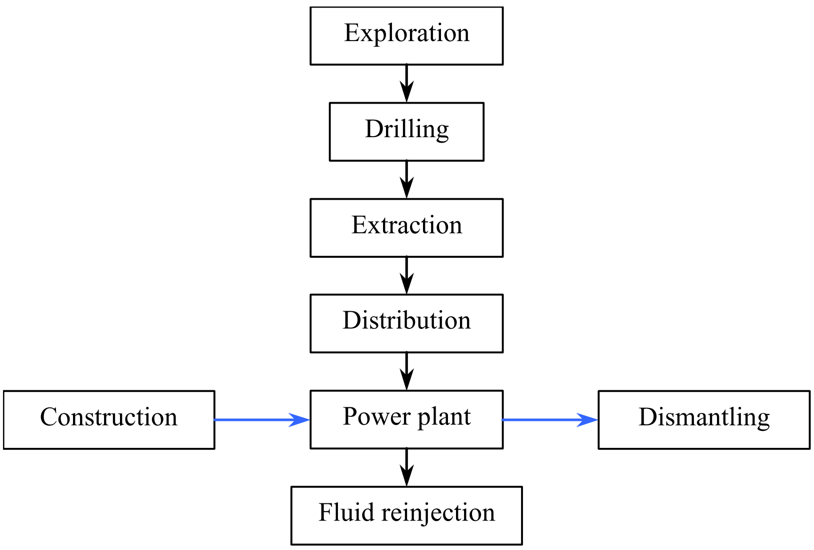
Types of geothermal power plants
(according to the temperature and pressure of the reservoir):

Hot water systems - using water between 50 and 100 °C, mainly for home space heating;
Liquid-dominated systems - containing pressurised water with temperature higher than 100 °C, for industrial use and electricity production;
Vapour-dominated systems - producing dry, super heated steam for electricity generation.

The lifetime of a geothermal power plant is estimated to be about 20 years or a little more. During operation, various maintenance operations are required for the well cleaning. The dismantling of a geothermal plant will be determined by the decreasing production of wells. The technical lifetime for a well is about 10 years.

- Fluid reinjection. the water from the flash separator is directly returned to the geothermal reservoir by injection wells, or cycled for other process or agricultural uses before re-injection. The steam is cooled to liquid form and then also re-injected into the geothermal reservoir.

Figure 2.17: Stages of the geothermal fuel cycle as they are mentioned in ExternE, Externalities of Energy, a research project of the European Commission, the first comprehensive attempt to use a consistent 'bottom-up' methodology to evaluate the external costs associated with a range of different fuel cycles [29].



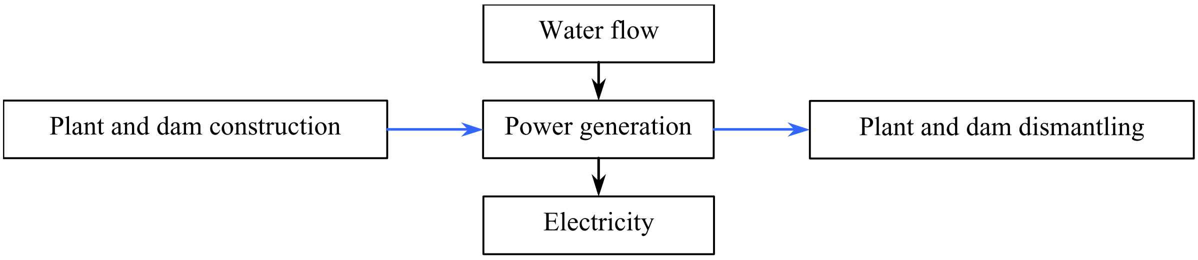
The main risks associated with geothermal activity come from spontaneous natural phenomena such as high temperatures and emissions of gases (e.g. hydrogen sulphide). However, technological incidents and accidents affecting the occupational health impact can occur during drilling operations for the construction of geothermal wells, as well as during the power plant construction, operation and dismantling. Finally, these regions also have to face geological hazards such earthquakes and volcanic eruptions, contributing to increasing the overall risk of installations. Thus, possible rupture of wells and/or damages to the facilities during a seismic event must be taken into consideration.

Among the different energy options investigated in the present report, geothermal is indeed the energy source that presents the closest relation between technological risk and natural hazards (*natechs*[3]). [29, 30]

2.4.3 Hydro

Hydro power covered 2% of the world's primary energy supply during 2002, contributing, with a production of 2,676 TWh, which corresponds to 16% of the world electricity generation in the same period [3].

Figure 2.18: Stages of the hydropower fuel cycle considered for Greece in ExternE, Externalities of Energy, a research project of the European Commission, the first comprehensive attempt to use a consistent 'bottom-up' methodology to evaluate the external costs associated with a range of different fuel cycles [4]. Stages such as construction and dismantling of power generation plant, including also dam, are the intersection point of the power plant life cycle.



The hydro fuel cycle is very simple and divided into [2, 4]:

- Water flow. This is the source of energy to drive machinery to produce useful power. Water flowing in rivers or through canals – pressured or not – from a reservoir, can provide such source of energy.
- Power generation, with plant and dam construction and dismantling. The power generation is done through hydraulic turbines - like Pelton, Kaplan, Francis – where the kinetic energy of water is used to produce mechanical energy to drive an electric generator. Dam and canals are considered as part of the power plant installation.

  Four different types of dams can be distinguished (see Figure 2.19).

[3] A natech disaster is a technological disaster triggered by a natural hazard. The technological disaster can include damage to industrial facilities, energy installations, and other lifeline systems (water supply systems, hospitals, etc.) [49].

Figure 2.19: Types of dams.

Hydro

Four types of dams

'Earth' and 'Rockfill': These are embankment dams whose fill material is earth or rock. They are placed with sloping sides and normally are more long than high.

'Gravity': A gravity dam is constructed of concrete and/or masonry and relies on its weight for stability.

'Arch': An arch dam is built of concrete or masonry curved in plan so as to transmit the major part of the water load to the abutments.

'Buttress': This is a watertight dam supported at intervals on the downstream side by a series of buttresses.

- Electricity. This is the final output of the hydro generation process, which is delivered to the final users through the transmission and distribution network.

According to ENSAD database, the risk associated with hydro power may arise during dam construction and during operation. Considering the period between 1930-1996, the higher percentage of dam failures occurred after 5 years of operation (about 38%), followed by failures during the first five years of operation and during the first filling (about 24%), and failure during construction (about 12%) [2]. Dam failure rates are also subject to the type of dam.

2.4.4 Solar

Solar energy can be divided into *solar thermal energy*, mainly used for water heating, and *solar photovoltaic*, applied for electricity generation.

Data from IEA-SHC (International Energy Agency-Solar Heating and Cooling Programme) published in 2004, refer to a global solar thermal installed capacity of 70 GW-th for the end of 2001 [50].

The photovoltaic market worldwide had a growth rate of 30% or more in 2003, reaching the highest ever level in PV cell and module production with 744 MW [31]. At the end of 2003 the electricity produced from photovoltaic installations in the EU-15 was about 0.48 TWh/a [19]. The solar resources in Europe, in terms of average yearly global irradiation on a horizontal plane, are evaluated 1096 kWh*m^2/year, a value that increases to 1130 kWh*m^2/year if only built-up areas are taken into consideration [32].

The investigation through the solar chain will focus only on the photovoltaic use of solar energy.

Figure 2.20: Stages of the photovoltaic module life cycle as modelled on the basis of information from [4, 11, 33].

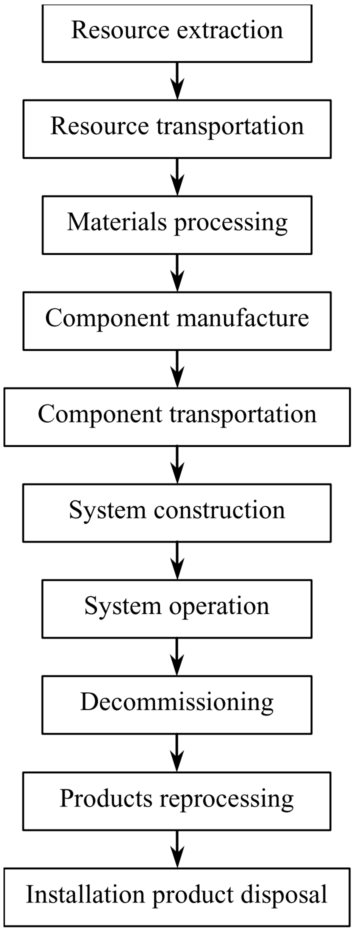


Figure 2.20 describes the photovoltaic module life cycle, including all related steps ranging from material extraction, silicon purification, wafer, panel and laminate production, mounting structure with about 30 years of operation to the final dismantling [34, 35, 36]:

- Resource extraction. The resources extracted are mainly aluminium, silica sand, quartz, tellurium, copper, indium, gallium and other dangerous elements like cadmium and arsenic [51]. At this stage of the life cycle it is also important to mention the preparation of other dangerous chemical compounds, like, for example, silane.
- Resource transportation. This process includes the transportation stage to the site where the resource is processed or used.
- Materials processing. Solar cells can be of different types: monocrystalline silicon and polycrystalline silicon (x-Si, the most diffuse types), amorphous silicon (α-Si), cadmium telluride (CdTe), copper indium selenide (CIS) and gallium arsenide (GaAs) (more expensive and used in special applications). Referring at this stage to crystalline silicon cells, which are the most popular, different processes are used to reach the final silicon cell to be used in modules. The production of metallurgical grade (MG) silicon, with a purity of about 99%, is based on carbothermal reduction of silica sand using petrol coke, charcoal and wood chips as reduction agents. Main emissions of this process are CO_2, SO_2 and trace elements emitted with SiO_2 dust. MG silicon is purified into:

   - *electronic grade (EG) silicon* in the Siemens process via reaction to trichlorosilane,
   - *off-grade silicon*.

  EG silicon is molten and a growing crystal is slowly extracted from the melting pot to constitute a monocrystalline silicon block (Czochralski monocrystalline silicon).

- <u>Component manufacture</u>. PV module manufacturing includes the following operations:
   - *Cell sawing*: silicon columns are sawn into wafers of about 300 μm;
   - *Bus printing and connection*: bus connections are printed on the cells, then the tabbing process solders normally two tabs on the busbar of the cell;
   - *Cell stringing*: single cells are connected in series to increase the power output. Electrical connection of thin-film cells is an integral part of the cell fabrication. In cadmium telluride and amorphous silicon cells the connection from back to front contacts is made by layers deposited to the front substrate (front glass substrate, transparent conducting oxide, solar cell layer and metallic layer as back contact). In copper indium selenide and amorphous silicon based on flexible film cells the process is similar but with a reverse sequence, starting from the back contact;
   - *Cell encapsulation*: to protect cells against mechanical stress, weathering and humidity, strings of cells are embedded in a transparent bonding material, that constitute also an electrical insulation. There are three types of encapsulations: ethylene vinyl acetate (EVA), Teflon and casting resin. The encapsulation is made through a lamination process, using EVA or Teflon;
   - *Framing*: modules can be with a frame (normally aluminium) or frameless.
- <u>Component transportation</u>. This stage is dedicated to the transport of components from the manufacturing site to the place of operation, including also personnel.
- <u>System construction</u>. Panels and laminates are mounted on the top of houses (slanted or flat roof systems) or integrated into facades in building integrated photovoltaic applications, or can also be grouped together in large field installations.
- <u>System operation</u>. Normal lifetime of a PV system is about 25-30 years, with maintenance costs about 1% of the installation cost.
- <u>Decommissioning</u>. This includes the entire operation of dismantling the whole installation or only changing old modules.
- <u>Products reprocessing</u>. Parts like metal, glass and silicon are recycled and reprocessed.
- <u>Installation product disposal</u>. After recycling, the remaining parts are incinerated or landfilled.

The solar chain analysed cannot be defined as a ‘fuel cycle’, as far as no fuel is actually involved, but represents only the stages of the life cycle related to construction, use and dismantling of the solar power plant, in which the main components are PV modules or panels. The fuel involved in the solar fuel cycle is sunlight. A similar situation is reported for the wind chain, where the fuel has to be considered the wind.

Photovoltaic electricity generation is a zero-emission process regardless of which technology (materials and manufacturing process) is used.

The only hazard concerning module operation can be related to toxic emissions in case of large externally fed industrial fires.

The highest environmental, health and safety hazards affecting the solar energy source are associated with the manufacture stage of solar cells. Table 2.2 shows the most important dangerous substances used in the manufacturing process and the safety issues related to the different type of solar cells [37].

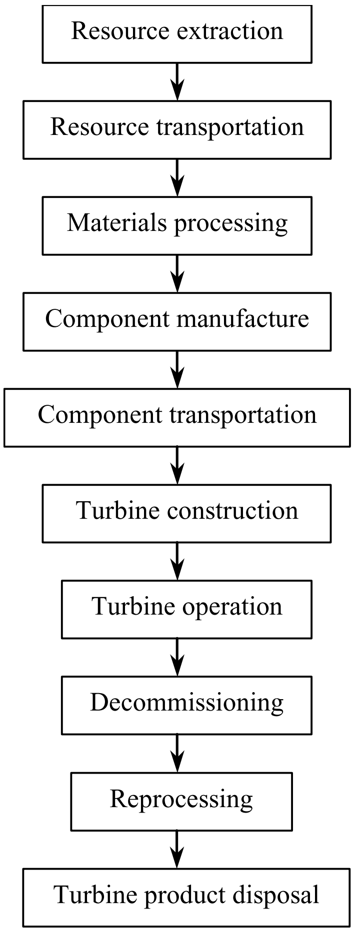
Table 2.2: Main dangerous substances and safety issues related to the PV modules manufacturing stage.

Cells	**Most important dangerous substances used**	**Safety issues**	
		Occupational health and safety	**Public health and environment**
Crystalline silicon (x-Si)	Hydrofluoric acid Nitric acid Alkalis Dopant gases (e.g. phosphorous oxychloride)	Chemical burns Toxic fumes inhalation Corrosion Irritation	No public health issues Environmental problems with slurries and solvents
Amorphous silicon (α-Si)	Silane Hydrogen Dopant gases (e.g. phosphine)	Fire and explosion hazard Pulmonary, blood and kidney effects Irritation	Fire and explosion hazards (especially for silane bulk quantities) No environmental issues
Cadmium telluride (CdTe)	Cadmium compounds	Pulmonary edema Cancer Kidney effects Death	No public health issues Environmental problems with manufacturing waste and module disposal
Copper indium selenide (CIS)	Copper compounds Indium compounds Selenium compounds Tellurium compounds Hydrogen selenide Hydrogen sulfide	Fire hazard Toxic fumes inhalation Irritation Pulmonary effects	Hazard from release of hydrogen selenide (1 ppm is immediately dangerous to life) Environmental problems with manufacturing waste and module disposal
Gallium Arsenide (GaAs)	Hydride gases (arsine and phosphine) Arsenic compounds	Toxic fumes inhalation Fire hazard Blood, kidney and lung effect Cancer	High hazard for transport of arsine by tube trailer (failure of 1 tube can be catastrophic) Environmental problems with manufacturing waste and module disposal

2.4.5 Wind

Wind is a renewable energy resource that can be converted into useful electric power through wind turbine. At the end of 2003, the cumulative global installed capacity of wind energy reached 40,301 MW [38]. For the same period, the electricity produced from wind turbines in the EU-15 was about 50.8 TWh/a [19]. Data from EWEA show that the total capacity installed at the end of 2003 was 28,440 MW in EU-15 and 28,542 in EU-25 [52]. Assessments confirm that the world's wind resources are extremely large and well distributed across all regions and countries. The total available resource technically recoverable is estimated to be about 53,000 TWh/a, a value twice as large as the projection for the world's entire energy demand in 2020 [39]. A scheme of the wind turbine life cycle is portrayed in Figure 2.21.

Figure 2.21: Stages of the wind turbine life cycle considered for Denmark in ExternE, Externalities of Energy, a research project of the European Commission, the first comprehensive attempt to use a consistent 'bottom-up' methodology to evaluate the external costs associated with a range of different fuel cycles [4].



The wind chain of Figure 2.21 can be described as follows [40, 41]:

- Resource extraction, Resource transportation and Materials processing. These three stages include raw material extraction, transportation and processing. The raw material taken into consideration are those necessary to have high density polyethylene plastic, oil and grease, copper, aluminium, fibreglass, steel, concrete, paint and computer component material.

- Component manufacture. The manufacture process of all different component of a wind generator covers the nacelle (and all its components inside, e.g. generator, gear box), blades and hub, steel foundation component, tower parts and control system at base.
- Component transportation. Dimensions of a wind turbine are such to make it impossible to transport the turbine already assembled. All components need to be transported to the site where the wind generator will operate. The transportation can be by rail, mainly by truck, and, if necessary, by helicopter. Shipping is necessary for offshore applications.
- Turbine construction. Includes all the operation of assembling and erecting the wind turbine.
- Turbine operation. The turbine operates according to wind availability and wind speed. Normally the power generated is directly dependent on the wind speed, however not proportional to it: between the cut-in wind speed (3-5 m/s) and the nominal or rated wind speed (11-16 m/s), it increases with the cubic of the wind speed. When wind speed is above nominal level, the power cannot be increased, because this would lead to overloading of the generator. The power output is controlled through the aerodynamics of the rotor, with a stall control or a pitch control approach. When the cut-off wind speed (17-30 m/s) is reached, the rotor stops automatically to prevent damages.
- Decommissioning. Is the process of dismantling the wind turbine when its life is over. After decommissioning no permanent changes to the environment have occurred. Some components of the wind generator can be re-used, while some others are recycled or disposed.
- Reprocessing. Many of the turbine’s component can be recycled. The main environmental problem associated with wind power are the rotor blades, which at this stage cannot be recycled, but are used in inferior applications, such as road pavements.
- Turbine product disposal. This stage groups all parts that cannot be recycled or re-used and are disposed in landfills.

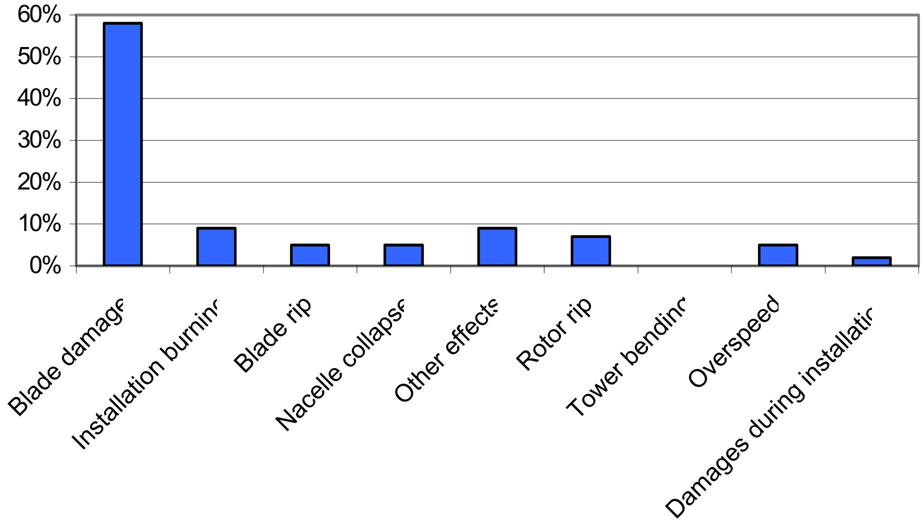
The wind chain previously analysed cannot be defined as a ‘fuel cycle’, as far as no fuel is actually involved, but represents only the steps of the life cycle related to the construction, use and dismantling of the wind power plant, constituted by one or more wind turbines. The fuel involved in the wind fuel cycle is the wind itself. A similar situation is reported for the solar chain, where the fuel has to be considered the sunlight.

Taking into consideration the mortality rate associated with wind energy related activities, the majority of fatal incidents can be attributed to construction activities, when installing, moving or removing wind turbines, including also operation and maintenance of the turbine [42].

Technical damages affecting wind turbines can include loss of blades, other structural failures or can be caused by lightning (see Figure 2.22 for spectrum of possible failure types).

As turbines become larger and are often installed in populated areas, the consequences of failures such as a faulty blade ejected by the tower can raise the risk for the public.

Figure 2.22: Share of wind energy related incidents according to the German WMEP database from ISET as reported in [43].



Risk analysis for off-shore wind turbines needs to cover the possibility of ship collision or damage to the grid connection. However, off-shore units, because of their reduced accessibility, are generally expected to have better remote control options and improved reliability [44], notwithstanding much higher maintenance problems and associated costs.

2.5 Hydrogen Technologies

Compared to other cases analysed in this report, hydrogen is not an energy source but an energy carrier, to be considered at the same level as heat or electricity. Interactions between energy sources and energy carrier (case of hydrogen) are illustrated in Figure 2.23. Hydrogen can be used to produce electricity, but also electricity can be used to produce hydrogen. Hydrogen technologies are now approaching the market as a possible future energy solution, often with the argument of "green energy". However, hydrogen occurs almost exclusively locked in other compounds and is only as clean and "green" as its source [47]. Figure 2.24 shows the various stages of the hydrogen chain.

Figure 2.23: Energy source versus energy carrier - case of hydrogen

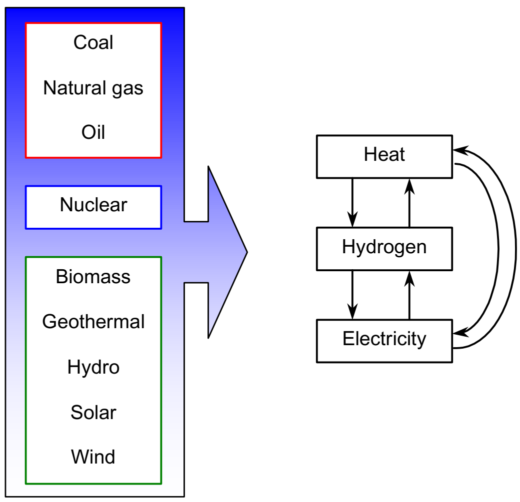
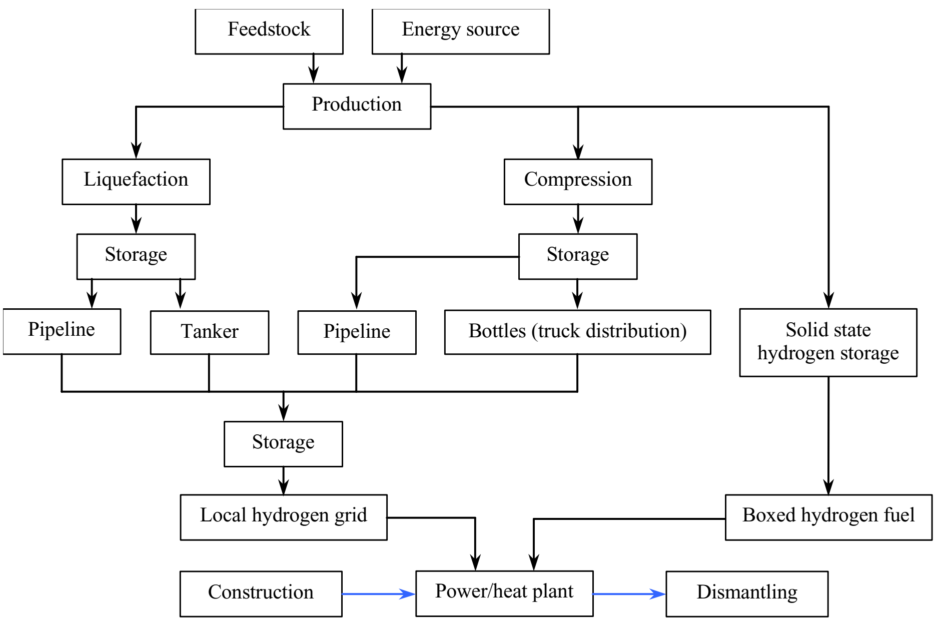


Figure 2.24: Stages of the hydrogen fuel cycle as from references [29, 45, 46].



The steps of the hydrogen fuel cycle are [45, 47]:

- Feedstock. Hydrogen can be extracted from different raw feedstocks, such as fossil fuels (coal, natural gas and oil), biomass (lignocellulose, starch, vegetable oils, black liquor), waste material (municipal solid waste, stack gases, waste water) and water.
- Energy source. To produce hydrogen, an auxiliary energy source is needed for the process. Energy source options are: thermal (fossil, renewable, nuclear), electricity (fossil, renewable, nuclear) and photolytic (solar).
- Production. Hydrogen production processes can be divided into thermal, electrochemical and biological (Figure 2.25).

Figure 2.25: Hydrogen production processes

Hydrogen Production Processes

Thermal processes
Reforming (steam reforming and partial oxidation)
Gasification
Pyrolysis

Electrochemical processes
Electrolysis
Photoelectrochemical

Biological processes
Photobiological
Aerobic fermentation
Anaerobic fermentation

- Liquefaction/Compression/Solid state hydrogen storage. To be stored or transported, hydrogen needs to be processed. Compression leads hydrogen from 50 bar for stationary storage, to 350-700 bar for transport purposes. Liquefaction needs to cool down hydrogen at –253 C with a highly energy intensive process (energy equalling 30-40% of that in the fuel is needed). Hydrogen can also be absorbed into metal hydrides and carbon nanostructures to obtain a solid form of storage for transportation, or can be 'chemically stored' in methanol or diesel.
- Storage. Compressed hydrogen in pressure tank or bottles can be stored, for long periods, in underground caverns, or above ground for frequent turn-over. Liquid hydrogen, because of its low temperature, needs to be stored in properly insulated tanks.
- Pipeline/Tanker/Bottles/Boxed hydrogen fuel. These are some examples of container or way of transportation for hydrogen. Hydrogen transportation is possible by roadway, rail, ship and airplane, but the most easy and cheap on long distance is by pipeline. Existing networks cover about 700 km in the USA and about 1500 km in Europe.
- Local hydrogen grid. According to a recent EC-JRC study [53], the use of local pipeline networks would start between 2015 and 2030 under the assumption of a fully-fledged hydrogen economy. Hydrogen distribution would start with regional

medium pressure pipelines, in parallel with the existing natural gas network, and in the long term parts of the natural gas distribution system would be converted for hydrogen use. The scenario tend to converge with the findings of the US Department of Energy, which assumes the presence of integrated central-distributed networks for the next future up to 2040.

- Power/heat plant, with construction and dismantling. Hydrogen use can be in combustion techniques and in fuel cells. In a long term vision of the hydrogen economy, fuel cells will be a mature, cost-competitive technology in mass production. Advanced, hydrogen-powered energy conversion devices, such as combustion turbines and reciprocating engines, will probably enjoy widespread commercial use.

As hydrogen production is always associated with the use of another energy source, as shown in Figure 2.23, it is important to highlight that a complete view in the consideration of risks from hydrogen implies also the consideration of risks rising from the energy source involved in hydrogen extraction.

The aerospace sector has the highest level of experience in dealing with hydrogen, therefore it can offer the most reliable source of information. In [48] from NASA is indicated that industrial and aerospace accidents from the use of hydrogen have occurred and this analysis indicates the following factors are of primary importance in causing system failures:

1. Mechanical failure of the containment vessel, piping or auxiliary components;
2. Reaction of the fluid with a contaminant;
3. Failure of the safety device to operate properly;
4. Operational error.

The main source of hazard is thus identified as hydrogen leaks.

Even if hydrogen is non-toxic, classified as a simple asphyxiant, and is not listed as a carcinogenic substance, there are different important hazards associated with it, characterised as:

- Chemical – hydrogen-air mixtures are highly flammable. After ignition, flame acceleration processes could cause fast turbulent deflagrations, even transition to detonations. Fast turbulent deflagrations and detonations have the potential for severe destructions;
- Physiological – frostbite, respiratory ailment and asphyxiation;
- Physical – phase changes, component failures and embrittlement.

3 Development of a General Scheme for Fuel and Life Cycles

3.1 Introduction and Explanation of the Development Concept

To reach a general scheme for all energy fuel and life cycles adaptable to every chain, it is necessary to collect existing and analyse as many fuel and life cycles as possible to find out all possible stages and their potential overlaps. The general scheme for ERMON has been developed with the intention to be as simple as possible, but not simplistic; thus, it is necessary to group where possible different steps of the same single fuel or life cycle into one more general but exhaustive.

The scheme developed fits to every single chain, to some of them completely, while some others will leave some steps empty. The scheme has been developed with main attention to fuel cycles and plant life cycles.

The main idea is that, however and whatever complicated a single chain could be, it can always find an allocation of all its steps into this general scheme.

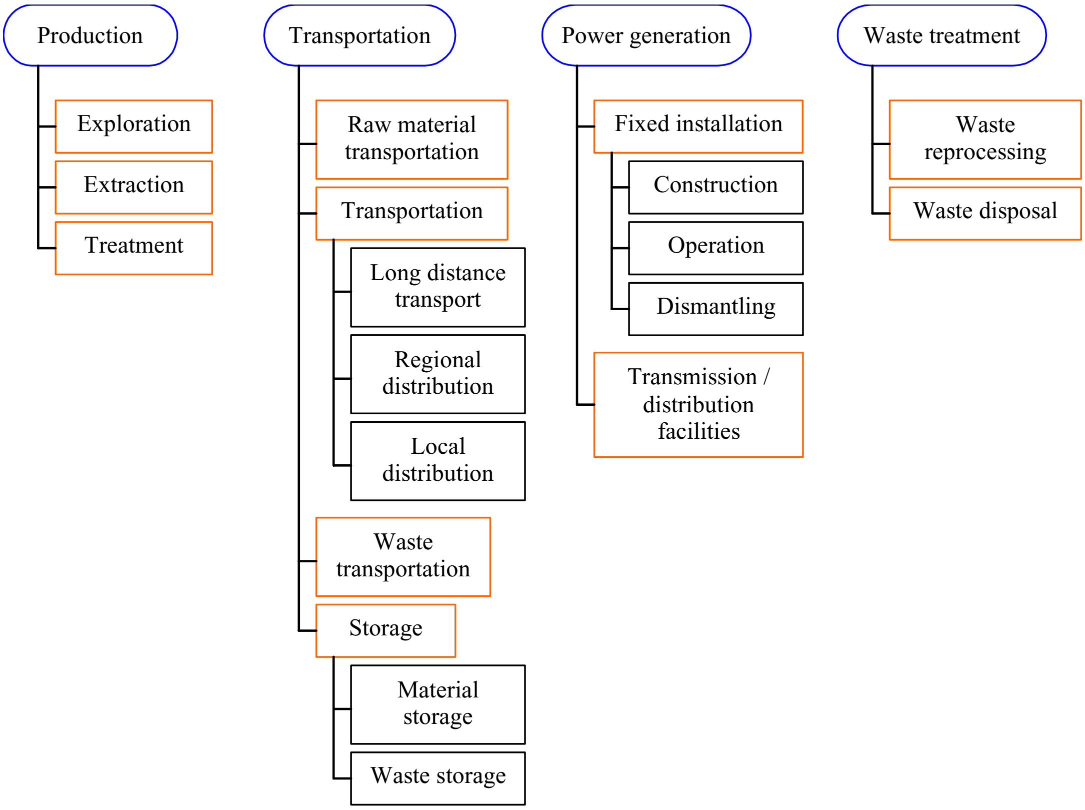
3.2 General Scheme

The general scheme developed is presented in Figure 3.1.

The scheme is characterised by four main steps:

1. **Production** - is related to all the operations of production of the subject in analysis (it can be production of a fuel, as well as a component or a material).
2. **Transportation** - includes the operation of transport of raw material, final product or waste. Storage has been considered as a part of the transportation, as the stored material is waiting to be transferred to another intermediate place or to the place of use.
3. **Power generation** - is the power plant, including the plant installation and the transmission and distribution facilities.
4. **Waste treatment** - is the final step in the chain, receiving waste from the power plant as well as from other production activities. Waste can be treated or can be sent to a final disposal.

Figure 3.1: Stages of the general scheme for all fuel and life cycles.



These four main stages are then divided into corresponding sub-steps to have a more clear specification of the chain. The sub-steps are:

Production

- Exploration – is the procedure of identification of the resource or the location where is very likely to find it. This step mainly includes geographical and geological investigations.
- Extraction – is the process to make the resource available for next transformation or use. Activities like mining, drilling or collecting are included in this phase.
- Treatment – is the step in which the final product to be used, that can be a fuel or a component, is prepared, or in some case created, and made available for direct use or for transportation. This stage includes steps such as petroleum refinery, as well as purification, compression or liquefaction of natural gas, biomass residue processing or bio-fuels production, as well as photovoltaic modules manufacture or wind turbine manufacture.

Transportation

- Raw material transportation – is the link between extraction and treatment of the resource.
- Transportation:

- Long distance transportation – transportation between different countries or different continents. This step can include high pressure natural gas pipeline, as well as oil barge transportation.
- Regional distribution – is a transportation between different regions of the same country.
- Local distribution – is a local transportation, mainly restricted to the area of use. Pipeline transportation mainly includes low pressure pipeline.

- Waste transportation – is the transportation of waste which can be generated at different levels in the chain. For example, nuclear waste can be transported in special container.
- Storage:
    - Material storage – is the storage before material or fuel use. Part of this stage can be the hydro reservoir, the storage of hydrogen in pressure or insulated tank, the storage of nuclear fuel in special container or in the nuclear power plant.
    - Waste storage – this step can be in the place of production or constitute an intermediate storage before waste final disposal.

Power generation

- Fixed installation:
    - Construction – this stage includes all the operations of preparing the area of construction and building the power plant or the power installation.
    - Operation – is the operative part, including functioning and maintenance for the power generation.
    - Dismantling – groups all the operations of dismantling the installation and bringing the area in the same environmental conditions as before. Material recycling and disposal related to the power installation are also included in this step. Dismantling procedures can be very expensive, like for nuclear power plant, and the monetary resources necessary for the operations are built up during the lifetime of the installation.
- Transmission/distribution facilities – this step includes all the facilities (pipeline, cable, etc) for heat and electricity transmission and distribution.

Waste treatment

- Waste reprocessing – includes the operations of recycling materials or fuels (e.g. nuclear fuel), or treating wastes to reduce their hazardousness.
- Waste disposal – is the final allocation of wastes in landfills or in dedicated deposits.

The application of the developed general scheme to the ten different energy sources analysed in the previous chapter is presented in the Appendix. The application is made with the aspect of a matrix in which the different steps of the chain are filled with respect to the single fuel or life cycle.

The application demonstrates that the scheme developed is applicable to fuel cycles (coal, natural gas, oil, nuclear, biomass, geothermal, hydro, solar, wind, hydrogen), as well as life cycles (solar modules and wind turbine production).

4 Conclusions

Ten different energy technologies have been analysed for the purpose of this report – coal, natural gas, oil, nuclear, biomass, geothermal, hydro, solar, wind and hydrogen. According to their characteristics, chains investigated in the context of energy systems can be distinguished into fuel cycles and life cycles. To allow a fair evaluation of the total energy supply cycle, it is important to carry out comparison among similar elements in the two different categories, and take all the results into consideration for a comprehensive and clear total view.

The analysis of the ten different energy chains has led to the development of a ***general scheme*** applicable to all fuel and life cycles. This scheme has gone through a reiteration process to fine tune the general scheme to all the above-mentioned energy chains resulting in the matrix shown in the Appendix.

The results of this analysis serve as the base for the ERMON project, which will help to compare the results of any existing risk study and incident/accident statistics for different energy systems across all steps in their specific fuel cycle or life cycle chains [55].

The next phase of the ERMON project is to identify appropriate European ***energy technology risk indicators*, ** aiming at:

- consistent comparison of different energy technologies,
- consistent evaluation of the safety risks of energy technologies including not only an evaluation of possible incidents/accidents, but also an assessment of the impacts from the energy generation and use,
- support to decision makers in better understanding risk-cost-benefit scenarios to best identify and prioritise areas where action is required,
- better communication of safety risks to stakeholders (general public, decision makers, industry associations, utilities, etc.).

Appendix: The Life Cycle Matrix

Stages of the life cycle			Fossil technologies			Nuclear technologies	Renewable technologies							Hydrogen technologies
			Coal	Natural Gas	Petroleum		Biomass	Geothermal	Hydro	Solar	Solar (PV modules)	Wind	Wind (turbines)	
Production	Exploration		Geological investigation	Geological investigation	Geological investigation	Geological investigation	N.A.	Geological, hydrogeological, geophysical, and geochemical investigation	Geographical / geological investigation	Geographical investigation	N.A.	Geographical investigation	N.A.	N.A.
	Extraction		Coal mining	Well drilling, pumping	Well drilling, pumping	Uranium mining	Biomass collection	Drilling	N.A.	N.A.	Feedstock and mineral collection	N.A.	Feedstock and mineral collection	Feedstock collection
	Treatment		Size reduction of mined coal; coal cleaning; coalification (bio-physical-chemical degradation); conversion into liquid or gas	Removal of hydrocarbon and non-hydrocarbon elements; liquefaction / compression	Refinery	Milling, transformation, conversion, enrichment and fuel fabrication	Residue processing, biofuels production	N.A.	N.A.	N.A.	Material processing, component manufacture	N.A.	Material processing, component manufacture	Hydrogen production from feedstock (with other auxiliary energy sources); liquefaction / compression
Transportation	Raw material transportation		Truck, railcar, barge	Upstream pipeline, tanker	Pipeline, ship tanker; short / long distance	Special container by ship, rail, truck	Residue transport	N.A.	N.A.	N.A.	Truck, rail	N.A.	Truck, rail	Pipeline, barge, railroad tank cars, rail, truck
	Transportation	Long distance transport	Railcar, barge	High pressure pipeline	Pipeline, barge, railroad tank cars	Special container by ship, rail, truck	Truck, ship	N.A.	N.A.	N.A.	Truck, rail, ship, plane	N.A.	Truck, rail	Pipeline, barge, air transportation
		Regional distribution	Railcar, barge	High / medium pressure pipeline	Pipeline, railroad tank cars, tank cars	Special container by rail, truck	Truck, ship	N.A.	N.A.	N.A.	Truck, rail	N.A.	Truck, rail	Pipeline, barge, truck
		Local distribution	Railcar	Medium / low pressure pipeline	Truck	Special container by truck	Truck	Pipeline	Water flow, canal, pipeline (also pressurised)	Solar concentrators	Truck, rail	N.A.	Truck, ship, helicopter	Local hydrogen grid, truck
	Waste transportation		Truck	N.A.	Tank cars	Special container by ship, rail, truck	Waste and ashes road / ship transport	Fluid reinjection	N.A.	N.A.	Truck	N.A.	Truck, ship, helicopter	N.A.
	Storage	Material storage	As necessary	As necessary	As necessary storage tank and local terminal	In special container and in the nuclear power plant	As necessary for energy consumption (close to plant)	N.A.	Dam construction and reservoir creation	N.A.	N.A.	N.A.	N.A.	As necessary pressure tank, insulated tank, solid compound
		Waste storage	After production and power generation stages	N.A.	Sludge' storage	Intermediate storage	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Power generation	Fixed installation	Construction	Power plant construction	Power plant construction	Power plant construction	Power plant construction	Power plant construction	Power plant construction	Power plant construction	Solar system manufacturing and installation	Power plant construction	Turbine manufacturing and assembling	Power plant construction	Power plant construction
		Operation	Power plant operation	Power plant operation	Power plant operation	Power plant operation	Power plant operation	Power plant operation	Power plant operation	Power plant operation	Power plant operation	Power plant operation	Power plant operation	Power plant operation
		Dismantling	Dismantling procedures, material recycling and disposal	Dismantling procedures, material recycling and disposal	Dismantling procedures, material recycling and disposal	Dismantling procedures, material recycling and disposal	Dismantling procedures, material recycling and disposal	Dismantling procedures, material recycling and disposal	Dismantling procedures, material recycling and disposal	Dismantling procedures, material recycling and disposal	Dismantling procedures	Dismantling procedures, material recycling and disposal	Dismantling procedures	Dismantling procedures, material recycling and disposal
	Transmission / distribution facilities		Electricity / heat distribution facilities	Electricity / heat distribution facilities	Electricity / heat distribution facilities	Electricity / heat distribution facilities	Electricity / heat distribution facilities	Electricity / heat distribution facilities	Electricity distribution facilities	Electricity / heat distribution facilities	Electricity distribution facilities	Electricity distribution facilities	Electricity distribution facilities	Electricity / heat distribution facilities
Waste treatment	Waste reprocessing		Plant flue gas and ashes recycling	N.A.	Sludge' processing / incorporating	Reprocessing and conditioning	Ashes recycling	N.A.	N.A.	N.A.	Recycling	N.A.	Recycling	N.A.
	Waste disposal		Landfill	N.A.	Landfarm, combustion, underground injection	Final disposal / deposit, final geological repository	Landfill	N.A.	N.A.	N.A.	Landfill	N.A.	Landfill	N.A.

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Development of a General Scheme for Fuel Cycles and Life Cycles from all Energy Technologies as a Basis for the European Energy Risk Monitor (ERMON)

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Abstract

In the context of the Energy Risks Monitoring (ERMON) project, the report presents the investigation of ten different energy technologies through their fuel/life cycle steps, with the purpose to develop a general fuel/life cycle scheme as the basis to allow a cross comparison among various energy systems.

The mission of the Joint Research Centre is to provide customer-driven scientific and technical support for the conception, development, implementation and monitoring of EU policies. As a service of the European Commission, the JRC functions as a reference centre of science and technology for the Union. Close to the policy-making process, it serves the common interest of the Member States, while being independent of special interests, whether private or national.

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